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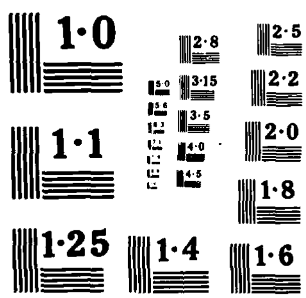
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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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AGARD ADVISORY REPORT No. 210

Technical Evaluation Report on the Fluid Dynamics Panel Symposium on Improvement of Aerodynamic Performance through Boundary Layer Control and High Lift Systems

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Advisory Report No.210

TECHNICAL EVALUATION REPORT

on the

FLUID DYNAMICS PANEL SYMPOSIUM

on

IMPROVEMENT OF AERODYNAMIC PERFORMANCE THROUGH BOUNDARY LAYER CONTROL AND HIGH LIFT SYSTEMS

by

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TECHNICAL EVALUATION REPORT ON THE FLUID DYNAMICS PANEL SYMPOSIUM ON IMPROVEMENT OF AERODYNAMIC PERFORMANCE THROUGH BOUNDARY LAYER CONTROL AND HIGH LIFT SYSTEMS

by

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1. INTRODUCTION

The AGARD Fluid Dynamics Panel organized a symposium on "Improvement of Aerodynamic Performance through Boundary Layer Control and High Lift Systems", in Brussels, Belgium from May 21 through May 23, 1984. The program committee was composed of M. l'Ing. Gen. C. Capelier, Professor Dr. Ing. K. Gersten, Professor J.J. Ginoux, Professor Dr. Ir. J.L. van Ingen, Professor M. Onorato, Dr. K.J. Orlik-Ruckemann, Professor E. Reshotko (Chairman) and Professor A.D. Young. The meeting announcement said that the aim of this symposium was to bring together the practitioners of various applications of boundary-layer control with those interested in the underlying fluid mechanics for the purpose of mutual learning and understanding. The symposium was to cover theoretical and experimental developments in the use of both traditional means of boundary layer control for external flow applications such as lift-augmentation, drag reduction and improved effectiveness of controls, and for internal flow applications such as air intakes and exit configurations. These boundary layer control techniques were to include: (i) shaping (geometry), (ii) suction and blowing, (iii) transverse blowing, (iv) vortex generators, (v) heating and cooling, and (vi) turbulent boundary layer manipulation. Special emphasis was to be given to high-lift systems including consideration of techniques of boundary layer control on characteristics of wings and wing-body arrangements that can involve flaps, slats and jets (blown flaps), and vortex flaps.

The final program of the symposium was arranged in six sessions: three on "High Lift Systems", two on "Drag Reduction", and one session on "Shock Wave Boundary Layer Interactions". Twenty five papers and a summary discussion have been published in the Conference Proceedings, AGARD-CP-365, May 1984. Approximately 140 people attended the meeting.

The purpose of this report is to present an overall survey and evaluation of the meeting, and to formulate some conclusions and recommendations based on the information presented.

2. DISCUSSION

2.1 HIGH-LIFT SYSTEMS

The development of a high-lift system for a specific flight vehicle and mission is an important task in aerodynamic design. This general topic of high-lift aerodynamics covers a large range of flight vehicle types and includes a number of different high-lift concepts. The majority of the papers in this section are limited however to a small but important segment of this wide spectrum of high-lift aerodynamics. The particular segment receiving most attention is the topic of mechanical high-lift systems for transport type aircraft. Although introduction of mechanical high-lift devices dates back to the early days of the airplane, and current trends in the latest generation of transport aircraft show no dramatic improvement in the concept of mechanical high-lift systems, the importance of this topic has not diminished with time. Detailed sizing studies show that total performance of transport aircraft is sensitive to improvements in the performance of high-lift systems.

The role of basic research in this area of high-lift aerodynamics is most often to analyse an existing design accurately and give understanding to underlying flow processes. This new understanding can then be applied to get improvement of aerodynamic performance through redesign without changing the basic design concept of mechanical high-lift systems. Such evolutionary development of mechanical high-lift systems, with basic research in fluid dynamics in a background role, has taken place during the last decades and is likely to continue into the forseeable future. To see where this continued evolutionary development might bring us we will take a closer look at the papers presented in the high-lift sessions.

The first paper presented by Butter, British Aerospace, concentrates on mechanical high-lift devices for transport type aircraft and examines recent progress on its development and progress on understanding the physics of high-lift flows. Likely future developments, such as "active" high-lift devices and computer control of aircraft to totally eliminate stall, are also suggested. The body of the paper however deals with current design techniques. After surveying both experimental and theoretical techniques and summarizing the deficiencies of several theoretical methods, it is pointed out that the state of the art of theoretical modelling does not meet all basic requirements in high-lift design. Problems that have to be covered by a successful 3-dimensional computational method are listed. To create such a 3-dimensional theoretical design capability is said to require a significant effort that would probably represent the main research in high-lift aerodynamics for the next decade or so.

Fiddes, Kirby, Woodward and Peckham survey results obtained from experiments in the RAE 5m low-speed pressurized wind tunnel. Two high-lift facets of the work in the 5m tunnel are described- (i) the separate effects of Reynolds and Mach number on the maximum lift of models of the Hawk and A300 aircraft, (ii) the optimisation of the slat position on two different high-lift research models. Tests on the A300 model and the Hawk model covering a Reynolds number range from 2 to 8 million show that maximum lift increases significantly with increasing Reynolds number at constant Mach number. These results demonstrate that one really needs to understand such maximum lift variations before the full scale transport-aircraft maximum lift can be extracted from the wind tunnel data at lower Reynolds numbers. In addition to this Reynolds extrapolation facet of model testing, the experimental investigating of slat position optimisation shows that a 3 percent gain in maximum lift can be achieved by optimising at a Reynolds number of 5 million in stead of 2 million.

Oskam at NLR and Laan and Volkers at Fokker describe some recent advances in computational methods to analyse high-lift flows. One of the questions is about the maximum pressure recovery that can be sustained

by a turbulent wake, which is a kind of applied-load versus allowable-load problem. The allowable load is the maximum pressure recovery that can be achieved by a wake; this maximum depends on the wake turbulence model. The applied load is the pressure induced by the inviscid flow, which changes substantially due to the displacement effect of the viscous wake. The example of a wing with double-slotted flap shows that the wing wake may play the key role in determining the maximum lift. Another question concerns locally supersonic flow in high-lift. Experimental results show high local velocities reaching a peak local Mach number of about 1.6 at a free stream Mach number of around 0.2; the full potential solution, obtained by applying the transonic panel method to the multi-component airfoil, agrees with the experimental data. These findings lead to the conclusion that it is imperative to include nonlinear compressible flow effects in any future high-lift design capability.

Porcheron and Thibert describe a detailed experimental investigation of the viscous flow around a tri-element airfoil mounted in the ONERA F1 wind tunnel. This experiment, carried out at a Reynolds number of 1.8 million, covers two flap deflections, 20 and 40 degrees. Detailed velocity profiles and turbulence measurements are presented for various stations such as slat trailing edge, wing nose, wing trailing edge and flap trailing edge. Comparisons between computation on the basis of a k-ε turbulence model and the experimental Reynolds shear stress measurements show that much work remains to be done. Note that the RMS-value of the velocity fluctuations is very high which may affect the accuracy of the Reynolds shear stress data, especially in the wing wake above the flap.

The paper by Hall and Suddhoo, University of Manchester, centers around a conformal transformation method to generate an orthogonal curvilinear grid for two and three element airfoils. The grids presented are possibly the best that may be obtained from conformal mapping methods without coordinate stretching. At the same time the quality of the grids may not be adequate for practical application. Especially the sparseness of the grid near the nose of the slat and near the trailing edge of the flap of a tri-element airfoil shows that the conformal transformation technique does have its shortcomings.

The design study reported by Van Egmond and Van den Berg, at NLR, concerns the application of a computational design method to improve a two-element airfoil. Wind tunnel measurements show that the redesigned slat-wing airfoil has a 30 percent lower drag coefficient than the original two-element airfoil at the same lift coefficient, and while the same maximum lift is achieved. This study is a clear cut example of improvement of aerodynamic performance of an existing configuration through redesign using a computational multi-element design method.

Discrete vortex modelling techniques are used by Solliman, Smith and Cheeseman, Southampton University, in a theoretical representation of circulation control by blowing. This modelling technique shows considerable success in simulating the lift produced from circular sections due to the jet, but simulating the drag is more difficult and would require additional modelling.

Losito and Torella, Italian Air Force Academy, propose a linear relation between the lift loss due to viscous effects and the amount of turbulent flow separation, i.e. the actual lift coefficient is modelled to be proportional to the turbulent separation location in terms of percentage chord measured from the nose of the airfoil. The conditions under which such simple relations may break down are not considered however.

Aerodynamic issues in the design of high-lift systems for transport-type aircraft are discussed in the paper of Dillner, May and McMasters. This review paper presents an outline of low-speed/high-lift aerodynamic research at Boeing. One of the fundamental issues addressed is the availability and impact of new tools. One of the tools to design practical, efficient high-lift systems is a quasi-3D viscous flow computational methodology. This methodology is based on a 3-dimensional potential-flow lifting surface theory which is used to define critical sections located at "peaks" in the span loading of a high-lift wing. Viscous flow analysis of these critical 2-dimensional sections is used to define an "effective mean surface". The 3-dimensional inviscid lifting surface analysis is then repeated to take account of the viscous effects by using this "effective mean surface" for a multi-element wing with part span flaps. The results of this "effective mean surface" approach is a dramatic improvement in test-theory comparisons of span loading for high aspect ratio configurations. This combined 3-dimensional potential flow and 2-dimensional viscous flow analysis and design does represent a powerful tool. It has changed the high-lift design process from one that has relied largely on experience, intuition and experimentation to an improved one that relies on a combination of computation and experiment. At the same time progress on experimental techniques is reported also, such as the wake imaging system that produces wake total pressure survey data in the form of color photographic prints. This improved flow visualization technique allows a designer to diagnose complex flows, such as the shedding of large scale vortices and/or wakes from various components of a high-lift aircraft configuration. These new tools to design high-lift systems have not only changed the design process but can also lead to improved total performance of aircraft by reducing the mechanical complexity, and thereby the weight, for a given level of aerodynamic performance. The paper covers a wide scope of issues and reminds the reader that there is still progress to be made in the design of mechanical high-lift systems.

The last paper in this section on high-lift systems is an update of the augmentor-wing project, and is given by Whittley of de Haviland Aircraft of Canada. The augmentor-wing powered lift concept has been the subject of investigation since the late sixties. Application and project studies are currently being undertaken on a powered lift STOL transport and a powered lift STOVL support aircraft. The tools used in this project are wind tunnels and a demonstrator aircraft. Computational design techniques for these powered-lift flows are nonexistent as yet.

To conclude this section on high-lift systems it can be said that the papers indeed show that the importance of research in the area of mechanical high-lift systems has not diminished with time. The reasons are that (i) the performance of the high-lift system has a profound effect on the sizing and total performance of a typical transport, (ii) there is still room for improvement. One of the key tools needed to achieve such further improvement is a comprehensive 3-dimensional computational design capability. Looking at the progress made during the past decade and recalling the complex physics involved it seems reasonable to expect that substantial progress can be made in a decade or so. However before a successful 3-dimensional method becomes available as a high-lift design tool it will also be necessary to carry out high quality experiments to provide the basic data to guide the computational modelling, and to develop the appropriate turbulence models.

The general topic of high-lift aerodynamics covers not only transport-type aircraft with mechanical flap systems; however topics such as lift augmentation through boubdary layer control and powered lift concepts did not receive much attention during this symposium.

2.2 DRAG REDUCTION

The drag of aircraft can be divided into different components, the most important being the induced drag and the viscous drag. Most papers in this section address viscous drag reduction, and reduction of drag due to skin friction in particular. Two main routes are apparent in viscous drag reduction research: (i) one can strive to maintain laminar boundary layer flow, or (ii) one can try to manipulate the turbulence in the boundary layer such that a skin-friction drag reduction results. Both methods for viscous drag reduction were emphasized at the symposium.

The first paper in this section by Thomas, Lockheed-Georgia, contains a broad survey of the various techniques to reduce aircraft drag. The subjects treated are: skin friction drag reduction, induced drag reduction, afterbody drag reduction, interference drag reduction, while also the possible gains of innovative aircraft configurations are discussed. The reductions in lift-induced drag to be achieved by winglets and various other wing-tip devices are reviewed. Afterbody drag reduction is obtained by avoiding separation and minimizing the vorticity trailing downstream from the fuselage. The discussion on skin friction drag reduction by laminar flow control and turbulence manipulators supplements the two survey papers on these subjects later in this section. A detailed discussion of these subjects will be postponed. The present paper mentions as turbulence manipulators both so-called large-eddy breakup devices and surface riblets. As regards the latter, the drag reduction mechanism is querried, especially whether the drag reduction is really due to a change in turbulence structure in the near-wall region or simply a direct result of the different way the viscous (non-turbulent) fluid flows over the ribbed surface.

The second paper, by Arnal and Coustols of ONERA-CERT, is a more specialized one. It deals with the prediction of the transition from laminar to turbulent boundary layer flow on swept wings. The authors have been active for some time already in three-dimensional boundary layer transition work. In three-dimensional boundary layers additional roads to transition are through cross-flow instability and through leading-edge contamination. The various transition criteria are applied on a given profile at wing-sweep angles of 0, 20° and 30°. For swept wings cross-flow instability and leading-edge contamination are shown to play a role at the higher Reynolds numbers. It is argued that to avoid cross-flow instability, the favourable pressure gradient in the leading edge region should not be too large. The influence of suction on the transition position on the swept wing has also been investigated by computations.

Hirschel, MBB-München, presented a theoretical study of the three-dimensional turbulent boundary layer flow on an aircraft afterbody. Three different configurations of the upswept rear part of the fuselage have been computed and the separation behaviour on the three afterbodies is discussed.

A combined blowing and suction boundary layer control system is discussed in the paper of Wiedemann and Gersten, University of Bochum. Blowing is applied in the front part to reduce the skin friction and suction is apllied in the rear part of the body to avoid flow separation. The study is both experimental and theoretical. The experimental work is on a circular cylinder with blowing and suction.

Van Ingen, Blom and Goei reported on design studies of thick laminar-flow airfoils, which are being carried out at Delft University. Laminar flow is obtained by designing for regions with a favourable pressure gradient (natural laminar flow). Suction is applied, not to control the laminar flow, but to prevent turbulent boundary layer separation over the rear part of the airfoil. Large adverse pressure gradients exist in the rear part of their designs as a consequence of the aim to produce a large extent of laminar flow. The potential improvements, which can be obtained by combining natural laminar flow in the front and turbulent boundary layer control in the rear of the airfoil, have been established by computations for a number of airfoil designs. The performance improvements are shown to be attractive.

A considerable effort in viscous drag reduction technology is going on since the late seventies at NASA, Langley. The paper by Wagner, Maddalon and Fischer reviews the investigations on the practicality of different methods to maintain laminar boundary layer flow on wings. This includes natural laminar flow by favourable pressure gradients, laminar flow control by suction and hybrid solutions. The concept of drag reduction by laminarization is already old and it is well established that potential gains are large. The real problem is to develop feasible wing structures that meet the stringent requirements for surface smoothness, and to demonstrate the practicality during routine flight operations. In the investigations these aspects are emphasized as is evident from aircraft factory involvement in the work. Flight tests using existing aircraft with adapted wings or wing gloves have been and are being carried out. Progress in this field is in fact impressive and soon laminar flow control technology will have reached the stage that sufficient information is available to consider the application in an actual commercial airplane design.

The review paper of Bushnell, Anders, Walsh and McInville treats the extensive turbulent drag reduction research work now going on for some years at NASA, Langley. The research program includes twelve different approaches to drag reduction. The present paper summarizes the status of five approaches: large-eddy breakup devices, surface riblets, slot injection, turbulent spot generation and relaminarization. The first two approaches are the most successful up to now. Large-eddy breakup devices consist of one one or more ribbons parallel to the surface, which alter the turbulence structure in the outer region of the boundary layer. Measurements show that the skin friction downstream of such a large-eddy breakup device is reduced. In order to obtain a net drag reduction, however, the skin friction must decrease sufficiently to more than cancel the device drag. Consequently the relaxation behaviour of the turbulence and the associated downstream distance with a reduced skin friction plays a crucial role. At NASA a net drag reduction of 8% has been obtained with a large-eddy breakup device. These data were obtained at rather low Reynolds number and in a zero pressure gradient flow. The other successful approach is the application of streamwise surface riblets, which affect the flow in the near wall region of the boundary layer. Also with riblets a drag reduction of 8% has been demonstrated. It was further found that drag reductions are approximately additive when combining riblets and large-eddy breakup devices.

Poll and Watson in their paper describe an experimental study, carried out at NASA, Langley, on the effect of a small forward facing step in a turbulent boundary layer. Particularly the relaxation of the turbulent boundary layer downstream of the step and the validity of the law of the wall is investigated. The test results were disappointing from the drag reduction point of view.

Bertelrud, FFA, discusses an application of ribbons as a large-eddy breakup device on a real aircraft in flight tests. The ribbons were positioned at 15% chord downstream of the swept-wing leading edge. Reductions in skin friction behind the large-eddy breakup device were established by Preston tube and hot film gauge measurements. Some boundary layer velocity profiles were also measured, but these do not indicate a net drag reduction.

The last paper in this section is from Horstmann and Quast, DFVLR, Braunschweig, and Boermans, Delft University. The paper deals with the manipulation of laminar separation bubbles. Particularly for airfoils with large regions of laminar flow, the drag penalty associated with the presence of a laminar separation bubble at the end of that region may be substantial. It is shown in tests that by blowing small amounts of air from a row of orifices at the beginning of the laminar separation bubble, the occurrence of a bubble can be prevented and the drag can be reduced considerably.

Summarizing the presentations in this section, it is clear that worthwhile drag reductions are still well within reach but that further research is required.

Large gains can be achieved by maintaining laminar boundary layer flow. The information needed to judge whether the laminar flow is workable or not in routine flight operations is coming available at fast pace. It establishes a technology base for future industry exploitation of the laminar flow concept. Accomplishments to date indicate that potential benefits of extensive laminar flow on commercial transports may be achievable.

The available knowledge about turbulence manipulation schemes is much less complete. Many new ideas and different devices may still emerge in the future. Better insight in what the devices actually do to the turbulence would be of great help to direct this research. Even for the two more successful turbulence manipulators known up to now, ribbons parallel to the surface and surface riblets, the mechanism that causes the drag reduction is not well established. The measurement conditions of the tests carried out up to now with turbulence manipulators are also still very restricted. Most of the measurements were done at rather low Reynolds numbers and at zero pressure gradient. In the author's opinion it seems especially advisable to investigate the effect of large-eddy breakup devices at non-zero pressure gradient. Assuming that such devices particularly affect the turbulent shear stress in the outer region of the boundary layer, boundary layer calculations learn that the resulting drag reduction in adverse pressure gradient flows will be very small. This is because of the counteracting effects of the reduced skin friction and the increased boundary layer shape factor in adverse pressure gradients. In favourable-pressure-gradient flows the history effects are not large as the magnitude of the turbulence fluctuations increases in streamwise direction. This means that the relaxation length will be small, so that the net drag reduction may appear to be also disappointing in that case.

2.3 SHOCK WAVE BOUNDARY LAYER INTERACTIONS

Adverse effects due to shock wave boundary layer interactions arise in many different types of flow, such as transonic aerodynamics, supersonic air intakes and turbomachinary. The papers in this section consider various ways of applying boundary layer control to mitigate these adverse effects of shock wave boundary layer interactions.

The review paper by Delery, ONERA, is thorough in that it surveys a large body of experimental data on interactions and subsequently covers numerous ways to control shock wave boundary layer interactions. This paper emphasizes the physical description of the flow phenomena involved in 2-dimensional transonic and supersonic interactions. The control schemes discussed are: wall cooling, wall curvature, distributed suction, local suction, low-speed slot injection, tangential blowing, vortex generators and internal bleed for air intakes. Each of these techniques has its own advantages but also its drawbacks such as structural complexity. Whether or not the advantages of a certain control scheme outweigh the drawbacks is said to depend very much on the type of problem at hand.

An extreme example of application of boundary layer control to shock wave boundary layer interaction can be found in the paper of Laruelle, Sans and Lefebvre. These authors discuss the results of an experimental study on a two-dimensional air intake, with the boundary layer removed by an internal bleed. Tests were performed in the supersonic wind tunnel S2 at ONERA. The goal of this study is to extend the operating range of an existing air intake optimized for a Mach number of 2. The results show that optimisation of the internal bleed geometry leads to improved air intake performance over an extended Mach number range.

A more subtle way to control the interaction between an oblique shock wave and a turbulent boundary layer is analysed by Lee and Leblanc, CEAT, Poitiers. They study the effect of distributed suction on the reflection of a weak oblique shock wave. At moderate suction levels the roughness of the porous wall causes a significant increase in the thickness of the upstream boundary layer. At high suction levels, such that the boundary layer is already sucked into the porous wall upstream of the interaction, an inviscid type of reflection results.

The application of shock wave boundary layer control to improve the off-design performance of supercritical airfoils is presented by Thiede, MBB-Bremen and Krogmann and Stanewsky, DFVLR-Göttingen. The experiments are carried out in a transonic wind tunnel using a supercritical airfoil section, at a Reynolds number of 2.5 million and at Mach numbers ranging from 0.6 to 0.86. The experimental results confirm the favourable influence of boundary layer control, mitigating the adverse effects due to shock wave turbulent boundary layer interaction. Substantial off-design drag reductions, up to 40 percent, are achieved by boundary layer ventilation in the shock region by means of a double slot with a plenum underneath. This arrangement results in injection upstream and suction downstream of the shock. The understanding of this control mechanism is by no means complete, so that further investigations are necessary. Application on supercritical wings to improve the aircraft performance has not been discussed as yet.

The use of tangential slot-injection to influence transonic shock wave turbulent boundary layer interactions is studied by Inger, West Virginia University. In this study it is assumed that the shock boundary layer interaction is sufficiently far downstream of the injection slot such that tangential slot-injection mainly affects the shape of the turbulent boundary layer coming into the interaction. By modifying the analytical model of the incoming boundary layer profile in his non-asymptotic triple-deck flow model Inger is able to show that the increased boundary layer fullness due to injection causes a significant reduction in the upstream and downstream extent of the pressure rise at the wall. The skin friction level is increased both fore and aft of the shock except in the vicinity of the shock foot where the local value of the skin friction is actually reduced. Thus it is seen that tangential slot-injection reduces the streamwise extent of the interaction, thereby intensifying the local adverse pressure gradient with the consequence of actually hastening the onset of shock foot separation.

To conclude this section it can be said that the papers clearly demonstrate that there is significant interest in the control of shock wave boundary layer interactions.

3 CONCLUSIONS AND RECOMMENDATIONS

Of all possible means to control the boundary layer in external flow applications such as lift-augmentation, drag reduction and improved effectiveness of controls, and in internal flow applications such as air intakes and exit configurations, only a relatively small number were discussed at this symposium.

- In the section on lift augmentation the emphasis was on mechanical high-lift systems employing traditional means of passive boundary layer control by contour shaping and variable geometry. The presentations showed that the importance of research in this area has not diminished with time because (i) the performance of high-lift systems has a profound effect on the sizing and total performance of current transports, and (ii) there is still room for improvement in the implementation of traditional means of boundary layer control. Computational techniques are providing new tools for high-lift design.

- In the section on drag reduction the emphasis was shared by laminar flow control and manipulation of boundary layer turbulence. With regard to the first it is concluded that the information needed to judge whether the laminar flow concept is workable in routine flight operations is coming available at fast pace. Accomplishments to date indicate that the large potential benefits of extensive laminar flow on commercial transports may be achievable. The available knowledge about non-traditional ways to manipulate turbulence is fragmentary at the moment however. Better insight in what the various devices actually do to the turbulence would be of great help to direct this research in turbulent drag reduction. The effect of non-zero pressure gradient is one of the issues to be investigated.

- The section on shock wave boundary layer interactions showed that there is significant interest in the control of such interactions to mitigate the adverse effects.

The conference as a whole showed that the intention of the program committee to bring together the practitioners of boundary layer control with those interested in the underlying fluid mechanics for the purpose of mutual learning turned out to be very stimulating.

4 SYMPOSIUM PAPERS

4.1 HIGH LIFT SYSTEMS

1. Butter, D.J., Recent progress on development and understanding of high lift systems
2. Fiddes, S.P., Kirby, D.A., Woodward, D.S., Peckham, D.H., Investigations into the effects of scale and compressibility on lift and drag in the RAE 5m pressurised low-speed wind tunnel
3. Oskam, B., Laan, D.J., Volkers, D.F., Recent advances in computational methods to solve the high lift multi-component airfoil problem
4. Porcheron, B., Thibert, J.J., Etude detaillee de l'ecoulement autour d'un profil hypersustente. Comparaisons avec les calculs
5. Hall, I.M., Suddhoo, A., Inviscid compressible flow past a multi-element aerofoil
6. Egmond, J.A. van, Berg, B. van den, Design of an airfoil leading edge slat using an inverse aerodynamic calculation method
7. Soliman, M.M.E., Smith, R.V., Cheeseman, J.C., Modelling circulation by blowing
8. Losito, V., Torella, G., Turbulent bubbles behind airfoils and wings at high angle of attack
9. Dillner, B., May, F.W., McMasters, J.H., Aerodynamic issues in the design of high lift systems for transport aircraft
10. Whittley, D.C., An update of the Canada/USA augmentor-wing project

4.2 DRAG REDUCTION

11. Thomas, A.S.W., Aircraft drag reduction technology
12. Arnal, D., Coustols, E., Application des criteres bi et tridimensionnels au calcul de la transition et de la couche limite d'ailes en fleche
13. Hirschel, E.H., Theoretical study of boundary-layer control
14. Wiedemann, J., Gersten, K., Drag reduction due to boundary-layer control by combined blowing and suction
15. Ingen, J.L. van, Blom, J.J.H., Goei, J.H., Design studies of thick laminar-flow airfoils for low speed flight employing turbulent boundary layer suction over the rear part
16. Wagner, R.D., Maddalon, D.V., Fischer, M.C., Technology development for laminar boundary layer control on subsonic transport aircraft
17. Bushnell, D.M., Anders, J.B., Walsh, M.J., McInville, R., Turbulent drag reduction research
18. Poll, D.I.A., Watson, R.D., On the relaxation of a turbulent boundary layer after an encounter with a forward facing step
19. Bertelrud, A., Full scale experiments into the use of large-eddy-breakup devices for drag reduction on aircraft
20. Horstmann, K.H., Quast, A., Boermans, L.M.M., Pneumatic turbulators - a device for drag reduction at Reynolds numbers below 5×10^6

4.3 SHOCK WAVE BOUNDARY LAYER INTERACTIONS

21. Delery, J., L'interaction onde de choc-couche limite turbulente et son controle
22. Laruelle, G., Sans, C., Lefebvre, R., Intérêt de piège interne pour le fonctionnement dans un domaine étendu du nombre de Mach (1.8 -3+), d'une prise d'air bidimensionnelle
23. Lee, D.B., Leblanc, R., Interaction onde de choc oblique-couche limite turbulente sur paroi poreuse avec aspiration
24. Thiede, P., Krogmann, P., Stanewsky, E., Active and passive shock/boundary layer interaction control on supercritical airfoils
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Emphasis of the presentations and discussion on lift augmentation was on mechanical high-lift systems, while laminar flow control and boundary layer manipulation shared the session on drag reduction. Significant interest was also shown in control of shock wave boundary layer interactions to mitigate their adverse effects.

The Symposium and this evaluation were sponsored by the Fluid Dynamics Panel of AGARD.

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